

## Explosions of LBV and Post-LBV Stars

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**Abstract.** In this contributed talk I presented the observational evidence for supernova (SN) explosions of stars in the luminous blue variable (LBV) and the immediate post-LBV evolutionary phases. We now have compelling indications that two recent SNe of Type II-“narrow” (IIn) were the explosions of LBVs, including the direct identification of the progenitor LBV for one of these examples. A recent SN of Type Ic exploded as a helium star, two years after the powerful LBV outburst of its progenitor. These cases were also discussed by other presenters at this Workshop in some detail. I instead focus more on another example, SN 2001em, which was first identified as a Type Ib/c, but later evolved to Type IIn. I argue that the progenitor of this SN exploded as a Wolf-Rayet (WR) star, following an eruptive LBV phase. Furthermore, I suggest that two “SN impostors,” i.e., extragalactic massive stars observed to undergo pre-SN LBV eruptions (similar to  $\eta$  Carinae), may well have evolved to the WR phase in real time.

### 1. The LBV-SN Connection

The core-collapse supernovae (SNe) that arise from massive stars come in various types: The Type II, particularly the Type IIn, and the Type Ib/c. Smith, Leonard, and Elias-Rosa discuss SN types elsewhere in this volume. Questions that are still to be resolved: What are the progenitors of SNe IIn, what are the progenitors of SNe Ib/c, and are the evolutionary paths of these massive progenitors somehow related or connected? How do stars in the LBV and WR evolutionary phases come into these progenitor scenarios?

Evidence is emerging of a connection between some core-collapse SNe and LBVs.

#### 1.1. Indirect Evidence

The extraordinary luminosities of the SNe IIn 2006gy in NGC 1260 (Smith et al. 2007; Ofek et al. 2007, however, see Agnoletto et al. 2009) and 2006tf in an anonymous galaxy (Smith et al. 2008) appear to arise with the interaction of the SN shock with preexisting dense circumstellar matter (CSM) lost by the progenitor prior to explosion. (Another recent example may be SN 2008fz, Benetti et al. 2008, the peculiar SN II 2005ap was also highly overluminous, Quimby et al. 2007.) The amount of mass lost would need to be  $\sim 1\text{--}2 M_{\odot}$ , requiring extremely high mass-loss rates,  $\sim 0.1 M_{\odot} \text{ yr}^{-1}$ . Such parameters are suggestive of giant eruptions of very massive stars in the LBV phase, such as  $\eta$  Car.

## 1.2. Direct Evidence

In the case of SN 2005gl in NGC 266, a very luminous point source, with  $M_V^0 = -10.3$  mag, has, at least preliminarily, been identified in pre-explosion *HST* image data (Gal Yam et al. 2007). With such a high luminosity, it is not clear whether or not this is a single star; it could well be a compact star cluster. If it were a single star, the high luminosity would be consistent with a LBV near maximum brightness. This would be the first instance definitively linking LBVs to SNe. See the contribution by Leonard in this Volume for further discussion of this object.

## 2. Post-LBV Supernovae

Recent examples also exist of SNe that have occurred immediately following the LBV phase.

### 2.1. SN 2006jc in UGC 4904

The most spectacular case so far is of the Type “Ibn” SN 2006jc (Foley et al. 2007; Pastorello et al. 2007). The SN was a peculiar Ib stripped of both H and He, with spectroscopic signatures (e.g., the “narrow” emission line profiles) of SN shock interaction with a slower-moving He-rich CSM. The progenitor star was therefore likely in the carbon-rich WR, or WC, phase. The most amazing aspect was that it was preceded almost exactly two years prior to explosion by an  $\eta$  Car-like eruption! The progenitor must have evolved rapidly from the LBV phase, through the WN phase, to become a WC star at explosion. This implies that the star must have been very massive.

### 2.2. SN 2001em in UGC 11794

SN 2001em was discovered on September 20 UT (Papenkova & Li 2001), but was likely already detectable by then. It was spectroscopically classified as a SN Ic on October 20 (Filippenko & Chornock 2001). See Fig. 1. As part of a survey to observe SNe Ib/c at late times in the radio, to test the hypothesis that some of these SNe could be off-axis gamma-ray bursts (GRBs; see, e.g., Granot & Ramirez-Ruiz 2004), SN 2001em was detected as a highly luminous radio source with the VLA in 2003 October (Stockdale et al. 2004). The SN was subsequently detected by *Chandra* as a highly luminous X-ray source (Pooley & Lewin 2004). This is very unusual behavior for SNe Ib/c at later times. The unusual early-time optical light curve, which showed a much broader maximum than normal SNe Ib/c (e.g., SN 1994I), provided some indication that SN 2001em was peculiar; see Fig. 5.. Comparison with the photometric evolution of the unusual SN Ic SN 2005bf (Folatelli et al. 2006, see below) indicates that SN 2001em may have exploded a month prior to discovery.

What is most remarkable is that, from a spectrum obtained by Soderberg et al. (2004) on 2004 May 7, SN 2001em had transformed to a SN IIn! Broad  $H\alpha$  emission, with FWHM  $\sim 1800$  km s $^{-1}$ , which would be highly unusual for a SN Ic at late times, dominated the spectrum. We confirmed this spectral appearance from our own observation on 2004 December 12 with LRIS on the Keck telescope. See Fig. 5..

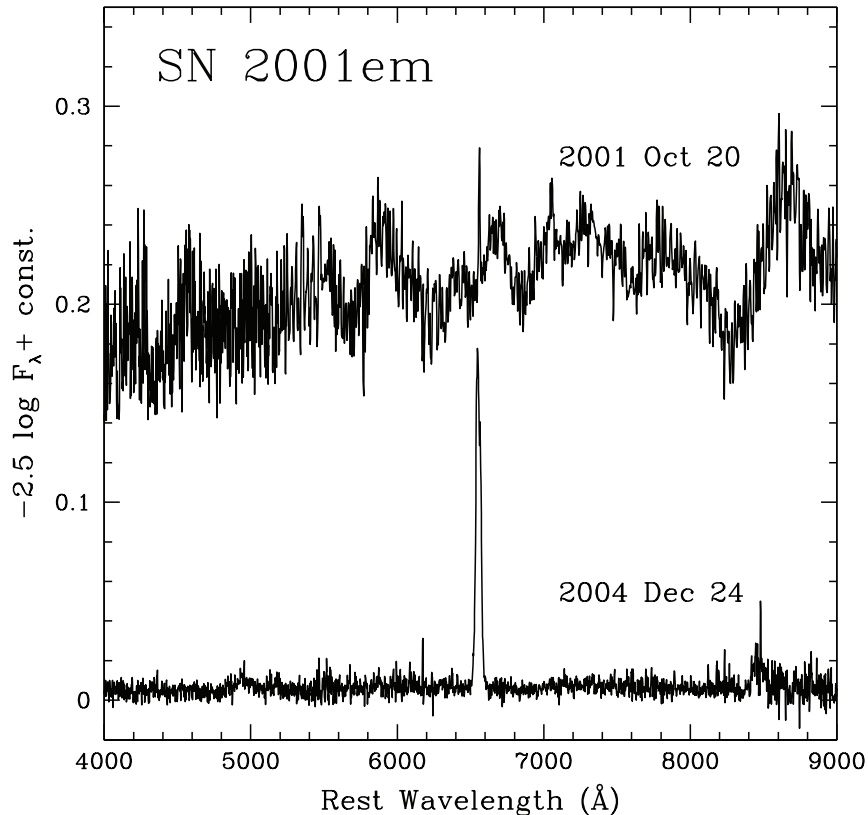


Figure 1. Spectra of SN 2001em, obtained with the Lick 3 m on 2001 October 20 UT (Filippenko & Chornock 2001) and with the Keck 10 m on 2004 December 24 UT.

In addition to the unusual observed spectral transformation, a number of authors have cast significant doubt on the off-axis GRB scenario via other arguments (e.g., Bietenholz & Bartel 2007; Schinzel et al. 2009). The strong H emission, as well as the luminous radio and X-ray fluxes, can more easily be explained as the SN shock interacting with and overtaking a dense circumstellar H envelope of comparable mass to the SN ejecta mass. The envelope is swept up and accelerated by a fast WR wind, which through Rayleigh-Taylor instabilities leads to clumpiness in the envelope. Chugai & Chevalier (2006), e.g., provided a model for a very dense, H-rich shell with mass  $M \sim 3 M_{\odot}$  with radius  $\leq 7 \times 10^{16}$  cm from the star. The shell was lost in a mass-loss episode at a rate of  $\dot{M} \sim 2\text{--}10 \times 10^{-3} M_{\odot} \text{ yr}^{-1}$  at  $\sim 1000\text{--}2000$  yr prior to explosion. Such a high-rate mass-loss event could be explained by binary interaction, but is more reminiscent of a superwind, or powerful eruption, from a LBV ( $\eta$  Car-like) star (Chevalier 2007).

### 2.3. SN 2005bf in MCG +00–27–005

Another event quite similar to SN 2001em is the unusual Type Ib/Ic SN 2005bf (e.g., Folatelli et al. 2006). Its optical properties, in particular, make it a ‘cousin’

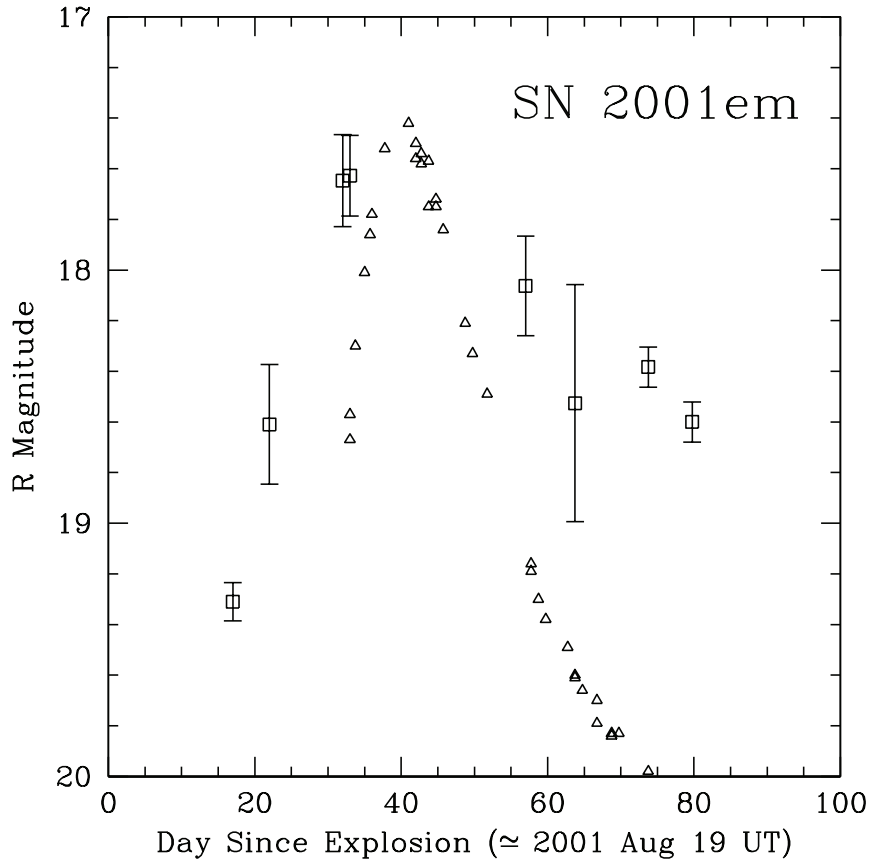


Figure 2. The  $R$ -band light curve for SN 2001em (*open squares*). The prototypical SN Ic 1994I is shown for comparison (*open triangles*; Richmond et al. 1996).

to SN 2001em. In fact, a Keck spectrum taken  $\sim 233$  days after explosion showed strong, broad  $H\alpha$ , very similar to what was observed for SN 2001em (Soderberg et al. 2005). Again, SN 2005bf may be an example of a very massive star which experienced a powerful LBV eruption before evolving to the WR phase prior to explosion.

### 3. Evidence of LBV to Post-LBV (WR) Evolution?

The behavior of the progenitors of SNe 2001em, SN 2005bf, and particularly, SN 2006jc is quite extraordinary. However, is it unique? Such  $\eta$  Car-like powerful eruptions, or outbursts, have been observed for a number of extragalactic events, which can be called  $\eta$  Car analogs. The energetics in these eruptions can rival that of true SNe; hence, they have been referred to as “SN impostors” (Van Dyk et al. 2000). Examples include SNe 1954J, 1961V, 1997bs, 1999bw, and 2000ch. See Van Dyk & Matheson (2009) for a review of the SN impostors. At least in the cases of SNe 1961V (e.g., Van Dyk 2005) and 1954J (Van Dyk et al. 2005)

the star survives the eruption as a highly luminous ( $M_V^0 \sim -7$  to  $-8$  mag) star. For the two examples below this appears not to be true.

### 3.1. SN 1997bs in NGC 3627

The spectrum of SN 1997bs resembled a SN IIn, however, both the luminosity ( $M_V \simeq -13.8$  mag) at maximum and the light curves, although smooth in nature, were unusual. Its color became progressively redder as well, from  $V-I \simeq 0.62$  mag at  $V$  maximum, to  $V-I \approx 3.4$  mag in late 1997. In *HST* imaging from 2001, SN 1997bs became much bluer, at  $V-I < 0.8$  mag ( $V$  [F555W]  $\sim 25.8$  mag and undetected at  $I$ ; Li et al. 2002). Most notably, the precursor of what was likely a powerful outburst was identified in a *HST* image from late 1994, with  $M_V \simeq -8.1$  mag. From this brightness and considering the range of supergiant spectral types, the star must have been hotter than F6; the SN 1997bs spectrum at maximum was also consistent with a hot precursor.

The flattening out of the late-time light curves implies that the star survived the eruption. By 2001 it had faded to 2.9 mag below its pre-eruption state, while returning to a bluer color. SN 1997bs could have been an actual SN and faded, as Li et al. (2002) suggested. However, with  $M_V^0 \sim -5.2$  mag in 2001, it is also possible that we had witnessed the precursor evolving from LBV outburst to the WR phase. The star's absolute magnitude and limit on the color from 2001 are both within the range of those of some WRs in the Galaxy (cf. Vacca & Torres-Dodgen 1990).

### 3.2. SN 1999bw in NGC 3198

SN 1999bw had spectral and luminosity characteristics similar to SN 1997bs (Filippenko, Li, & Modjaz 1999). Li et al. (2002) identified a  $V \simeq 24.1$  mag source in an *HST* image from 2001. A remeasurement of the position of SN 1999bw shows that this position differs by  $1''.0$  with that of the identified source—i.e., SN 1999bw has not been recovered since outburst to  $V \gtrsim 27.9$  mag, or  $M_V^0 \gtrsim -2.9$  mag, from *HST* images in 2006. Dust obscuration could well be responsible; however, although emission from dust was detected using *Spitzer* at the site of SN 1999bw (e.g., Sugerman et al. 2004), the infrared emission was no longer detectable in 2006. My speculation, although not nearly as evocative as in the case of SN 1997bs, is that, since the absolute magnitude limit on SN 1999bw is within the range for some WRs in the Galaxy and, particularly, in the LMC (cf. Vacca & Torres-Dodgen 1990), the precursor of SN 1999bw also may have evolved since outburst from the LBV phase to the WR phase.

## 4. Conclusions

My conclusions are:

- Evidence exists that at least one SN IIn arose from the explosion of a LBV star (presumably after a powerful eruptive episode).
- Indications are that some (two?) SNe Ib/c arise from the explosions of WR stars, which have evolved rapidly after a LBV eruption.

- At least three SN impostors, including  $\eta$  Car itself (!), have survived powerful  $\eta$  Car-like outbursts, or eruptions.
- Two SN impostors may have evolved rapidly after outburst to the WR phase—we may have witnessed this evolution in real time.
- All SN impostors should be continuously monitored—one day, soon, they too could explode.
- SNe Ib/c and IIIn should be observationally revisited at late times.

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